

Tools in Circular Building Environment

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Contributor: Lucas Caldas , , Romildo Dias Toledo Filho

The circular economy (CE) has become a trend because concern has arisen regarding the end of life of several products and the reduction of CO2 emissions in many processes.

circular economy

buildings

life cycle assessment

building information modeling

Materials passport

Digital tools

1. Introduction

The building sector is one of the major contributors to greenhouse gas (GHG) emissions, depletion of natural resources, and waste generation ^{[1][2]}. In this perspective, it is necessary to change the way cities, buildings, and their various elements are designed. For this, it is necessary to change the current linear way of thinking to a circular model, in which resource use efficiency is increased and waste and pollutant generation is reduced. With this vision, it is possible to make cities and buildings more inclusive and sustainable.

The circular economy (CE) model has gained attention in recent years from several productive sectors, including the architecture, engineering, and construction (AEC) industry ^{[3][4]}. There are different principles or strategies for implementing a CE model, including use of waste from other processes, reduction of natural resource consumption, prioritization of the use of renewable resources, deconstruction or design for disassembly project (DfD), design for performance, design for service life extension, construction virtualization, end-of-life reuse and recycling, etc. ^{[5][6][7]}.

When applied to the AEC industry, the CE model should encompass the entire life cycle of a product. It can include a material, a piece of furniture, a construction element (wall, floor, roof, etc.), or an entire building ^[3]. In addition, it is known that the construction sector is composed of several actors with different roles, such as developers, builders, designers, materials suppliers, building users, managers, etc. Thus, it is clear that the study of the CE concept applied to this sector tends to be complex, and some opportunities may not be fully explored.

Most studies in the literature regarding the CE applied to the construction sector have focused on the use of waste for materials production and reuse strategies, and many other strategies have not yet been explored in depth. In addition, few studies have focused on carrying out a quantitative analysis of the literature on the CE and AEC industry. Some of the research, such as that of Akanbi et al. ^[8], Akanbi et al. ^[9], and Honic et al. ^[10], has used tools, such as life cycle assessment (LCA), building information modeling (BIM), and materials passports (MP),

respectively, to facilitate the production process for circular construction products. However, it is still a research topic that needs to be further explored.

New research should include the evaluation of other tools that can help the implementation of CE strategies. Some strategies, such as waste management plans during buildings construction and buildings environmental certification schemes, e.g., leadership in energy and environmental design (LEED) or building research establishment environmental assessment method (BREEAM), have been used in the construction sector for some time. Recently, with the increase in interest in smart building development, the use of information and communication technology (ICT) has aroused great interest in research [11]. Therefore, augmented reality (AR) and virtual reality (VR) can be considered potential tools for a more sustainable building design development since they can lead to the virtualization of the construction sector.

In the literature, some review studies have already been published regarding the CE in the AEC industry. Gallego-Schmid et al. [12] evaluated the links between the use of CE strategies for climate change mitigation. López Ruiz et al. [13] reviewed different studies related to the CE and waste generated in construction and demolition activities. Foster [3] evaluated the use of CE strategies with a special interest in historic buildings. Hossain et al. [14] performed a systematic literature review to evaluate the implications, considerations, contributions, and challenges of the CE in the construction industry. These authors identified the existing trends and challenges in different parts of the process (design, materials selection, supply chain, business model, risk management, etc.) and actors. They observed that just a small percentage of studies focused on the environmental assessment and, when it is performed, the LCA is the most used tool. Ávila-Gutiérrez et al. [15] developed a framework aligned with the goals of the 2030 Agenda for Sustainable Development under the three pillars of sustainability and industry 4.0. Superti et al. [16] developed a framework for the construction and demolition sector that categorizes CE interventions into four parts: research and realize, implement, support, and enable, each considering the so-called 10R-strategies commonly used in the CE universe. Ogunmakinde et al. [17] assessed the link between the CE and the United Nations Sustainable Development Goals (SDGs). They observed that is essential to understand the relationship between CE strategies and the SDG in order to attain smarter construction and demolition waste management and that all stakeholders who generate waste have an important role in the transition to a circular model. Norouzi et al. [18] performed a quantitative scientific evolution analysis of the application of CE in the construction sector by the analysis of 7000 documents published between 2005 to 2020. They verified that researchers pay close attention to the following areas: sustainability, energy efficiency, renewable energy, LCA, and recycling.

However, there is still a knowledge gap in research focused on the use of different design, management, and execution tools for the production of more circular buildings that, at the same time, can reduce their GHG emissions. This gap is even greater when considering the seven tools selected in this research. It is possible to observe that most studies present frameworks linked to CE strategies but most of them do not offer ways to implement them considering the tools available in the sector.

Based on this context, researchers propose the following research question: “How can the use of different tools contribute to the implementation of CE strategies and simultaneously attain the reduction of GHG emissions?”

Therefore, the objective of this entry is to evaluate via the scientific literature how different tools used in the AEC industry can contribute to the mitigation of climate change in a CE environment with a focus on building life cycles and stakeholders.

2. Use of the Tools in a Circular Building Environment

Based on the literature that was evaluated, researchers developed a flowchart (Figure 1) that shows where in the life cycle of buildings the tools can be applied and how they can contribute to climate change mitigation, and consider two types of design: conventional and disassembly (DfD). Additionally, the chosen tools are correlated with the CE strategies (Figure 2) and building's stakeholders (Figure 3).

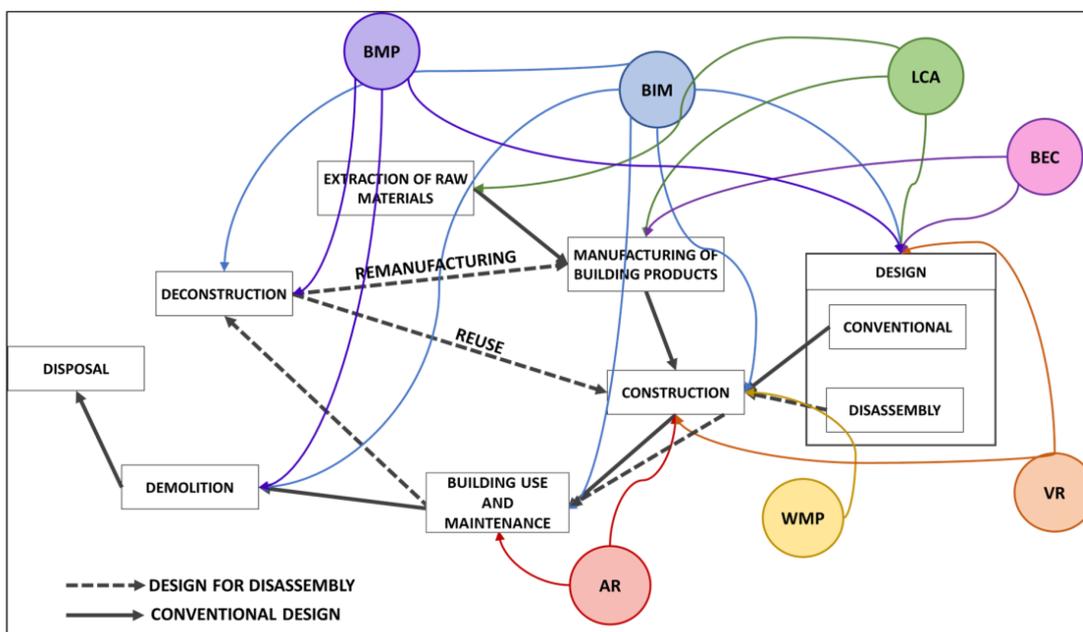


Figure 1. Use of the tools

throughout the life cycle of buildings. BIM—building information modeling. LCA—life cycle assessment. BEC—building environment certification. AR—augmented reality. VR—virtual reality. WMP—waste management plan. BMP—building materials passports. Based on Cruz Rio et al. [\[19\]](#).

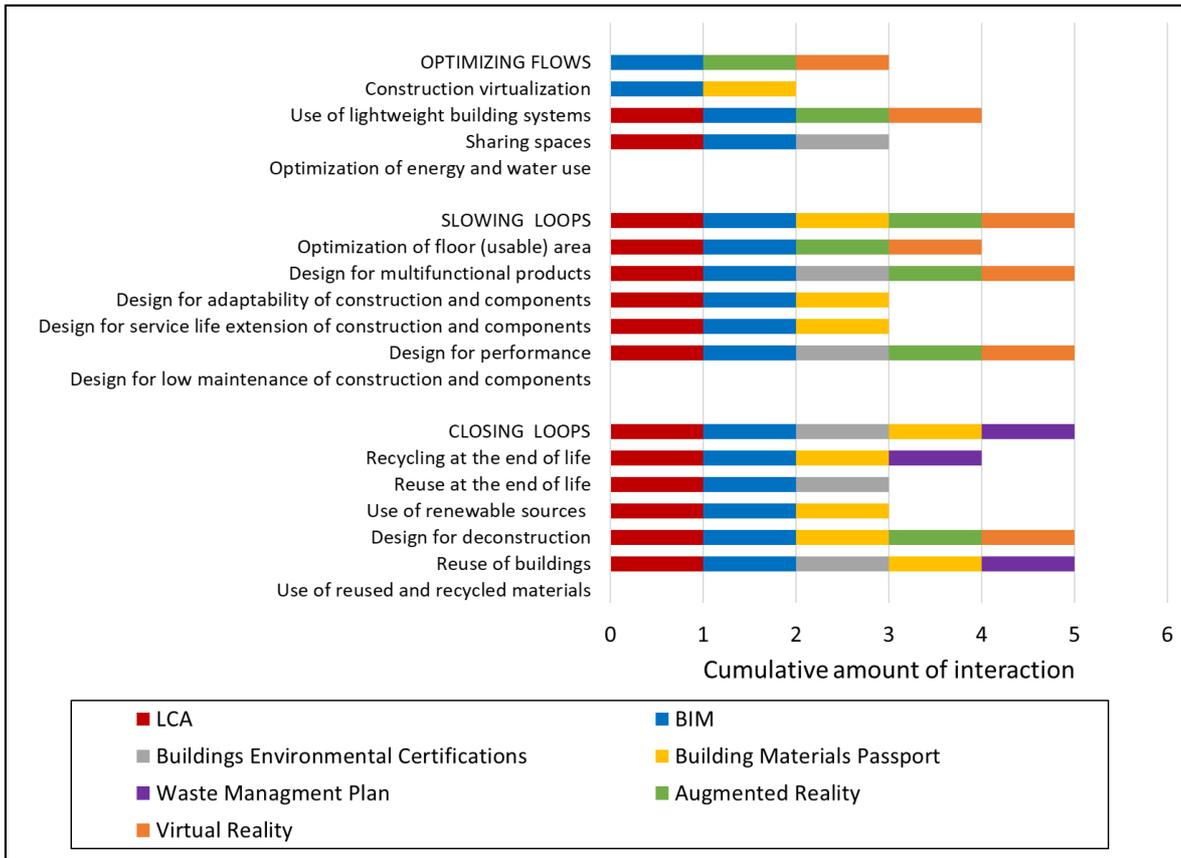


Figure 2. Use of

tools according to CE strategies.

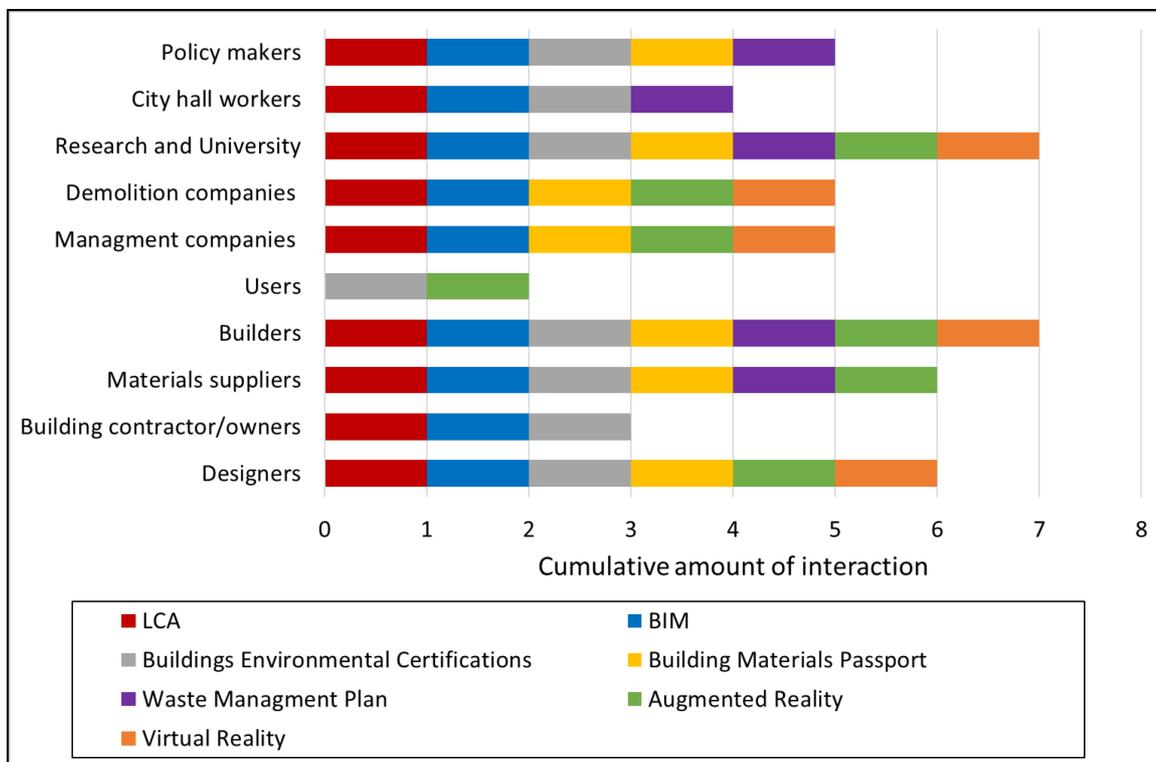


Figure 3. Use of

tools according to the building's stakeholders.

Based on how the tool contributes to each phase, it is possible to link each tool throughout the building's life cycle to an action recommended by the CE. It can be noted that the BIM and LCA are the most applicable. Through design for disassembly (DfD), within this built environment, there are possibilities beyond recycling. DfD enables the future disassembly (or deconstruction) of buildings and the reuse and remanufacturing of construction components that contribute to reducing the use of natural resources and energy and, thus, the reduction of climate change.

Considering the building's stakeholders, the constructors, researchers, and designers can be the main users and, consequently, those that most benefit from the use of the evaluated tools. The LCA and BIM, once again, showed themselves to be the most applicable. However, each tool that is applied to CE strategies brings benefits and contributions to one or more stages of the building's life cycle, whether in the conventional building design process or in the disassembly (or deconstruction) project and can reduce GHG emissions, as can be observed in the following definitions:

- (a) LCA: Enables the quantification of benefits when using reused and recycled materials, reusing buildings, adopting the practice of DfD, using renewable energies, recycling and reusing materials, and building elements at the end of life stage. With LCA, it is possible to transform all options and strategies into GHG emissions reduction and measure the increase or decrease according to different strategies and scenarios.
- (b) BIM: Facilitates the design process by adopting CE strategies through automation and can be easily integrated with LCA, BMP, and BEC, and with AR and VR for modeling virtual products. It also facilitates optimizing the use of energy and water simulations, and consequently, the related GHG emissions, which, in turn, ensures the better environmental and thermo-energetic performance of buildings. BIM is a tool that can be present in all stages of the building's life cycle (project, material production, construction, use, maintenance, and end of life).
- (c) BEC: Encourages the use of recycled materials and their reuse in projects, in addition to requiring the adoption of CE strategies that contribute to the mitigation of climate change. It also encourages the use of renewable resources such as wood and bamboo that can absorb CO₂, the main GHG. It encourages functional projects and the use of materials that have easy maintenance and higher quality. It also seeks to encourage the rational use of construction materials and systems with less energy and water expenditure, less waste generation, and consequently, the related GHG emissions.
- (d) BMP: Its use has significant advantages in the design and deconstruction phases because it provides valuable information about the materials and wastes. Thus, it facilitates the deconstruction process and the destination of materials and construction elements by identifying which materials have the potential for reuse and recycling. This information, which is provided from the materials, especially at the end of the building's life, is particularly important in order to estimate and reduce GHG emissions.
- (e) WMP: Its use can be highlighted in the construction and end of life phases by making it possible to manage and quantify the waste generation, and it permits the selection of the best end-of-life option for waste. The data generated with this tool enable the quantification of GHG emissions. The sorting process can facilitate the reuse and recycling and, consequently, the reduction in related GHG emissions.
- (f) AR and VR: These two can indicate elements of the building and construction in layers that facilitate the deconstruction process. The use of virtual models facilitates the evaluation of different strategies in the design

phase, enables the choice of products to be used in each stage, and finally, allows the use of virtual models—mainly in the design, construction, and maintenance stages of the building. If it is possible to exchange a physical product for a virtual one, the GHG emissions during the life cycle of the physical product are avoided. Based on the literature, researchers believe there is a trend towards the integration of the tools that use BMP with the tools that use BIM and LCA, as observed in Honic et al. [10]. In order to have a complete sustainability evaluation, with the evolution of the economic and social dimensions of LCA, the assessment will be more systemic. A scheme for the integration of the evaluated tools is proposed in **Figure 4**.

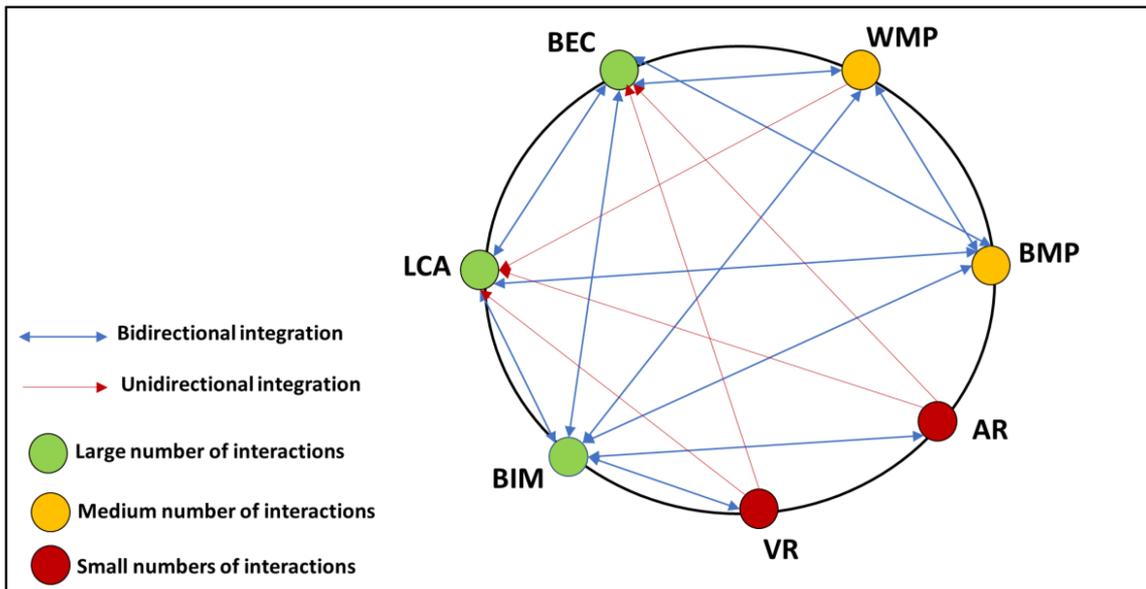


Figure 4. Integration

of tools. LCA—life cycle assessment. BEC—building environment certification. AR—augmented reality. VR—virtual reality. WMP—waste management plan. BMP—building materials passports.

It can be seen that the tools can be classified mainly in three groups, according to the number of interactions (in green, yellow, and red colors): (1) strategic approach (LCA, BIM, and BEC); (2) strategic and visual approach (BMP and WMP); and (3) technological and execution approach (AR and VR). The first group allows a more systemic and holistic intervention related to general management strategies on a macro level. The second one has a similar action but on an intermediate level. The third one is used for the implementation of certain actions on a micro level.

LCA presents interactions with all other tools and shows its potential for adaptability and as a facilitator when choosing CE strategies for quantifying and mitigating GHG emissions. The BIM tool also has many interactions and the fact that all of its integrations are bidirectional is highlighted. BIM delivers accurate quantitative information from the design phase to the end of the building's service life, thus enabling the application of other tools to enhance the measures, which can contribute to mitigating climate change.

The evaluated ICT tools, AR and VR, proved to have potential; however, so far, they have not been used (in the evaluated literature) in the context of sustainability and climate change mitigation (they have small numbers of interactions). The researchers expect this research and integration between tools to happen in the near future, as

long as this technology evolves and new sensors and software are made available for their best use in the sector. As shown in **Figure 4**, they can be linked mainly with LCA, BEC in a unilateral way, and BIM in a bilateral way.

It can be expected that shortly, all of these tools will be able to be used together, in a complementary way, with all the benefits for the production of circular economy buildings, though with a smaller amount of GHG life cycle emissions.

3. Recommendations for the Improvement of Tools

Based on the scientific evidence and the main objective of this research, which is the use of CE strategies and principles for mitigating climate change by reducing GHG emissions, researchers developed some recommendations for the improvement of the chosen tools (**Table 1**). These suggestions can be useful for the researcher, developers, and other stakeholders that use these tools.

Table 1. Recommendations for the improvement of tools in the context of the circular economy and climate change mitigation.

Tools	Recommendations
Life cycle assessment (LCA)	-Use in preliminary design stages linked with other tools. Specifically, for BEC in the use of EPDs.
	-Link the different aspects of sustainability (environmental, economic, and social).
	-Make the benefits related to avoided impacts mandatory due to recovery of waste or closed-loop end of life scenarios (reuse, recycling, or burning with energy recovery).
	-Make the quantification of biogenic CO ₂ mandatory for bio-based materials in order to account for the benefits related to the use of these materials for climate change mitigation.
Building information modeling (BIM)	-Define clear and standardized rules to avoid problems such as double counting of benefits, frontiers of the second-life system, etc. Similar to PEF (product environmental footprint) in the European Union.
	-Use in preliminary design stages linked with other tools.
	Development of a library of materials with information related to the level of circularity of the product (content of recyclable materials, potential for reuse or recycling at the end of life, etc.)
	-BIM software developers should create specific plug-ins related to waste management, circular product evaluation, design for disassembly (DfD), and the possibility of creating a building materials passport (BMP).
	-The BIM should be extended to an assessment tool beyond building boundaries, including the scale of neighborhoods and even cities (city information modeling). It is

Tools	Recommendations
	important to associate it with other tools such as the geographic information system (GIS).
Building environmental certifications (BEC)	-Create scores for other CE-related strategies that have not yet been considered (multifunctional projects, shared and collaborative projects, design for disassembly (DfD), end of life reuse and recycling, presence of materials passports, etc.)

es. Those

that were listed were based on the papers evaluated in the SLR and deserve special attention in order for researchers to have more possibilities for scientific and technological progress and innovation in the context of CE.

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